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APPLICATION FOR UNITED STATES LETTERS PATENT

FOR

SPIN DRIVEN RESISTORS AND NANOGATES

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TECHNICAL FIELD OF THE INVENTION

[0001] This application claims the benefit of U.S. Provisional Application Serial No. 60/411,923, filed on September 19, 2002, which is incorporated herein by reference.

[0002] This invention relates to spintronic devices. Specifically, this invention relates to spin driven resistors and spin driven nanogates.

BACKGROUND OF THE INVENTION

[0003] The term "spintronics" refers to a new generation of electronic devices that make use of the electron spin as well as its charge. It is anticipated that spintronic devices will have superior properties compared to their semiconductor counterparts based on reduced power consumption due to their inherent nonvolatility, elimination of the initial booting-up of random access memory, rapid switching speed, ease of fabrication, and large number of carriers and good thermal conductivity of metals. Such devices include giant magnetoresistance (GMR) and tunneling magnetoresistance (TMR) structures that consist of ferromagnetic films separated by metallic or insulating layers, respectively. Switching of the

magnetization direction of such elementary units is by means of an external magnetic field that is generated by current pulses in electrical leads that are in proximity

[0004] As used herein the term “resonance” shall mean the process by which the wave amplitude and probability are transferred between two degenerate states, in a manner analogous to the energy transfer between two harmonic oscillators. As used herein, the term “resonance absorption shall mean the absorption of radiation by an atom (or molecule) at a frequency corresponding to some transition between stationary states. As used herein, the term “resonance frequency” shall mean the frequency at which resonance absorption occurs; the difference between some pair of atomic energy levels divided by Planck’s constant.

[0005] One of the goals of the present invention to provide spin driven resistors and nanogates.

SUMMARY OF THE INVENTION

[0006] The present invention presents a novel approach for new types of “spintronic” devices called spin driven resistors (SDR) or spin driven nanogates (SDN). In a spintronic device of the present invention, a magnetic body is in electrical communication with two wires. Each of the wires is connected to a voltage source so as to place a potential across the magnetic body. The magnetic body has a resistance that is capable of changing when the magnetic body is subjected to an applied magnetic field while in the presence of an electromagnetic field. The ratio of change in resistance over resistance for the magnetic body is maximized when the

magnetic field is at the resonance frequency of the magnetic body for a given electromagnetic field. Increasing the power of the applied electromagnetic field increases the magnitude of the ratio of change in resistance over resistance. The magnitude of the ratio of change in resistance over resistance decreases with increasing temperatures.

[0007] In a preferred spintronic device of the present invention, the magnetic body comprises a material selected from the group of metallic and semi-conducting magnets. It is most preferred that the magnetic body comprise vanadium di-tetracyanoethanide ($V[TCNE]_2$).

[0008] It is preferred that a spintronic device of the present invention be held at a constant temperature while being subjected to the externally applied electromagnetic field and/or the externally applied magnetic field. It is more preferred that the externally applied electromagnetic field comprise microwave radiation. It is most preferred that the microwave radiation have an applied power in the range of about 1 mW to about 25 mW. It is further preferred that the externally applied magnetic field comprise a direct-current (DC) magnetic field.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] Figure 1 is a photograph of a 5μm coating of the organic $V[TCNE]_2$ magnet on a glass cover slide being attracted to a Co_5Sm magnet at room temperature in the air.

[0010] Figure 2 shows the magnetization (emu/mol) as a function of temperature showing ordering at 370K for the organic magnet shown in Figure 1 .

[0011] Figure 3 illustrates the chemical structure of tetracyanoethanide.

[0012] Figure 4 is a schematic level diagram for $V[TCNE]_2$ showing the half-filled π^*-band of $TCNE^-$ split into two non-overlapping spin-subbands.

[0013] Figure 5 illustrates derivative (a) and absorption (b) curves for 9.5 GHz EPR of $V[TCNE]_x$ at 2.02 mW of applied microwave power at 290K.

[0014] Figure 6 illustrates the $\Delta R/R$ versus applied magnetic field for applied 9.5 GHz microwave power of 2.02 mW applied to $V[TCNE]_x$ films at 290K.

[0015] Figure 7 illustrates the $\Delta R/R$ versus applied magnetic field for applied 9.5 GHz microwave power of 20.2 mW applied to $V[TCNE]_x$ films at 290K.

[0016] Figure 8 represents the 20.2 mW $\Delta R/R$ as a function of temperature from 275K to 298K.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT(S)

[0017] The present invention includes new types of "spintronic" devices that are termed "spin driven resistor" (SDR) or "spin driven nanogate" (SDN). These devices have potential as a platform technology for information storage and processing as well as in other uses. Examples include magnetic read heads and detectors.

[0018] In developing the spin driven resistor (SDR) of the present invention, a magnetic body was placed in electrical communication with two conducting wires. The wires were each connected to a voltage source so as to place a potential across the magnetic body. The resistance of the magnetic body was then measured, for example with a voltmeter. The magnetic body's resistance was monitored with the

voltmeter as the SDR was subjected to an externally applied dc magnetic field. Additionally, a time varying electromagnetic field acted upon the SDR. As the dc magnetic field is increased or decreased so as to pass the value of 'resonance' to occur so electromagnetic energy is absorbed there is a change in the resistance of the sample (increase or decrease), termed the spin driven resistance due to activation of the spin driven nanogate.

[0019] Metallic or semiconducting magnets with a substantial excess of one polarization of conduction carrier spin polarization over the opposite of spin polarization are preferred.

[0020] A spin driven resistor of the present invention was developed using the "half-semiconductor" $V[TCNE]_x$. Figure 1 is a photograph of a 5μm coating of the organic $V[TCNE]_2$ magnet on a glass cover slide being attracted to a Co_5Sm magnet at room temperature in air. Figure 2 shows the magnetization (emu/mol) as a function of temperature for the organic $V[TCNE]_2$ magnet shown in Figure 1. As can be seen from Figure 2, the organic $V[TCNE]_2$ magnet shows ordering at 370K. The chemical structure of tetracyanoethanide is shown in Figure 3. The newly achieved SDR is a spin-dependent quantum effect active at room temperature.

[0021] Figure 4 is a schematic diagram for $V[TCNE]_2$ showing the half-filled π*-band of $TCNE^-$ split into two non-overlapping spin-subbands.

[0022] Figure 5 shows the 290 K electron paramagnetic resonance derivative signal (a) measured for $V[TCNE]_x$ films (prepared via low-temperature (40° C) chemical vapor deposition) that are magnetic at room temperature. Also shown in Figure 5 is the absorption curve (b) that represents the power absorbed by the

sample. As expected it was found that the EPR (WHAT DOES EPR STAND FOR?) line shape and center field depend upon the angle of the $V[TCNE]_x$ films with respect to the applied magnetic field.

[0023] Figures 6 and 7 illustrate the percentage change in resistance at 290 K of the $V[TCNE]_x$ film as a function of the applied magnetic field for 2 mW and 20 mW of applied 9.5 GHz microwave power respectively. As the magnetic field sweeps past the field for resonance (3492 Oersted), the resistance dramatically increases. As seen in Figure 6, a $\Delta R/R$ of 1.3% is achieved for 2 mW of applied microwave power. The SDR increases nearly linearly to a $\Delta R/R$ of 10.5% for applied microwave power of 20 mW as shown in Figure 7. The shape of the $\Delta R/R$ versus magnetic field curve mimics that of the EPR absorption curve.

[0024] Figure 8 presents the $\Delta R/R$ as a function of temperature from 275 K to 298 K for a $V[TCNE]_X$ film subjected to 20.2 mW of microwave radiation. The $\Delta R/R$ decrease three-fold as the temperature is increased across this temperature range.

[0025] A proposed mechanism for spin driven resistor operation may be understood by viewing Figure 4. The $V[TCNE]_x$ is proposed to be a half semiconductor with a filled lower Hubbard energy band centered on the $TCNE^-$ sites (one electron per site). The magnetic exchange coupling of the spin S = 1/2 of $TCNE^-$ sites with the S = 3/2 of V^{2+} sites result in all of the sites in this lower Hubbard band being in the same spin direction. With x < 2, typical of samples made, the upper Hubbard band is assumed partly occupied with electrons with spin opposite to

that of the electrons in the lower Hubbard band due to the Pauli exclusion principle. The conductivity is by hopping among states in the upper Hubbard band.

[0026] It is further believed that at resonance, the applied microwave field flips some of the spins in the lower Hubbard band of localized states. These 'inverted' states then block passage of the spin (and associated charge) in the upper Hubbard band thereby increasing the resistance. In essence, each $TCNE^-$ becomes a "spin-driven nanogate". At finite temperatures some thermally reversed spins already exist. By lowering the temperature, the ratio of minority to majority spin sites decreases making the effect of spin flip due to resonant microwave field larger, in agreement with Figure 8.

[0027] The operation of spin driven resistors is sharply dependent on the applied magnetic field, with the magnetic field for SDR tunable by choice of applied resonance frequency. For example, use of ~ 20 MHz frequency would lead to SDR at ~ 7 Oe applied field for the $V[TCNE]_x$ based devices.

[0028] It is noted that SDR may have eventual application in a variety of spintronic devices including read heads and detectors that are very fast and operate at low power. The SDR phenomenon may also be used to modulate spin valve, spin tunnel junction, spin-LED, and spin-transistor devices by exposing the magnetic semiconductor or conductor layer to a time varying electromagnetic field and a dc magnetic field so as to pass through a resonance condition.

[0029] While the invention has been described in connection with what is presently considered to be the most practical and preferred embodiments, it is to be understood that the invention is not to be limited to the disclosed embodiment, but on

the contrary, is intended to cover various modifications and equivalent arrangements included within the spirit and scope of the appended claims, which are incorporated herein by reference.